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Inventor: Gregg A. Johnson

NOTICE

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WASHINGTON DC 20375

PATENT APPLICATION/TECHNICAL DIGEST PUBLICATION RELEASE REQUEST

FROM: Associate Counsel (Patents) (1008.2)
TO: Associate Counsel (Patents) (1008.2)

Via: (1) Gregg Johnson (Code 5673)
(2) Division Superintendent (Code 5600)
(3) Head, Classification Management & Control (Code 1221)

SUBJ: Patent Application/Technical Digest entitled: **"PASSIVE, TEMPERATURE COMPENSATED TECHNIQUES FOR TUNABLE FILTER CALIBRATION IN BRAGG GRATING INTERROGATION SYSTEMS"** Request for release for publication.

REF: (a) NRL Instruction 5510.40C
(b) Chapter 6, ONRINST 5870.1C

ENCL: (1) Copy of Patent Application/Technical Digest

1. In accordance with the provision of references (a) and (b), it is hereby requested that the subject Patent Application/Technical Digest be released for publication.

2. It is intended to offer this Patent Application/Technical Digest to the National Technical Information Service, for publication.

3. This request is in connection with Navy Case No. 82,373

8/14/00
(date)

BARRY A. EDELBERG
Associate Counsel (Patents)

FIRST ENDORSEMENT Date: 8/18/00

FROM: Gregg Johnson (Code 5673)
TO: Division Superintendent (Code 5600)

1. It is the opinion of the Inventor(s) that the subject Patent Application/Technical Digest (~~is~~) (is not) classified and there is no objection to public release.

Inventor's Signature

SECOND ENDORSEMENT Date: 23 August 2000

FROM: Division Superintendent (Code 5600)
TO: Classification Management & Control (Code 1221)

1. Release of Patent Application/Technical Digest (is) (~~is not~~) approved.

2. To the best knowledge of this Division, the subject matter of this Patent Application/Technical Digest (~~has~~) (has not) been classified.

3. This recommendation takes into account military security, sponsor requirements and other administration considerations and there in no objection to public release.

Dr. C. Hoffman, Acting Supt., OSD, Code 5600

Craig A Hoffman

Division Superintendent

THIRD ENDORSEMENT Date:

FROM: Head, Classification & Control (Code 1221)
TO: Associate Counsel (Patents) (1008.2)

1. This Patent Application/Technical Digest is authorized for public release.

Ina Smallwood

Head, Classification, Management & Control

Inventors: Johnson et al.
Serial No.

PATENT APPLICATION
Navy Case No. 82,373

PASSIVE, TEMPERATURE COMPENSATED TECHNIQUES FOR TUNABLE FILTER CALIBRATION IN BRAGG-GRATING INTERROGATION SYSTEMS

BACKGROUND OF THE INVENTION

Field of the Invention

Generally this invention pertains to a wavelength reference and calibration device, and more specifically to a fiber Bragg grating interrogation system for determination of Bragg grating wavelengths.

Description of the Related Art

There is a need for accurate measurement of Bragg gratings wavelengths that includes long-term and static strain monitoring on structures and determination of wavelengths in optical communications systems. There a number of systems that use the wavelength of fiber Bragg gratings to indicate the value of a measurand such as strain or temperature often at distributed points on a structure. In systems of multiple Bragg gratings -- especially in a single fiber -- bandpass filters that scan through a range of wavelengths are commonly employed. (**SEE**, Kersey et al.; A MULTIPLEXED FIBER BRAGG STRAIN SENSOR SYSTEM WITH A FIBER FABRY-PEROT WAVELENGTH FILTER; Optics Lett., Vol/18, Pg. 1370, 1993.) In some schemes, the control signal applied to the filter is used to determine the wavelength of the individual gratings. This practice depends on an estimated functional relationship between the filter control input and the wavelength location of the passband, a function that is not in practice linear or constant in time. For dynamic measurements a one-time calibration is often adequate, while for very low frequency measurements a real-time calibration is necessary for accurate determination of Bragg grating wavelength. Current filter calibration options include wavelength references such as temperature-isolated gratings (**SEE**, U.S. Patent No. 5,818,585) or the fringe pattern of a temperature-isolated Fabry-Perot cavity (**SEE**, U.S. Patent No. 5,892,582). In either case, the reference wavelengths are sensitive to changes in temperature and care must be taken to keep the gratings or cavity at a constant temperature.

SUMMARY OF THE INVENTION

The object of this invention is to provide an interrogation system for fiber Bragg gratings enabling accurate determination of Bragg grating wavelengths that is compensated for changes in temperature, if required.

This and other objectives are met by a passive, temperature compensated tunable filter calibration device for Bragg grating interrogation having a set of reference wavelengths, enabling accurate determination of Bragg grating wavelengths. There are two devices, first is a system that estimates the temperature of an array of gratings using an array of gratings bonded to a common host substrate and a single grating bonded to a material with different linear coefficient of thermal expansion, this is called a dual-substrate Bragg grating calibration system. Changes in a common temperature of the subsstrates is measured by monitoring the difference betweeen shifts of grating wavelength. As a filter is scanned from its lowest to highest voltage and the voltages are recorded. The second lowest wavelength corresponds to the grating attached to the differing substrate. The voltages are used to calculate the voltage-to-wavelength function for the scanning range of the filter. To compensate for variations in a calibration curve and temperature variations of the calibration array, the temperature is estimated and function recalculated at every pass of the scanning filter.

The second system uses a wavelength reference absorption cell, preferably a hydrogen-cyanide ($H^{14}C^{13}N$) type of wavelength reference absorption cell, that absorbs light at discrete wavelengths corresponding to the molecular vibrational mode frequencies of the gas. A wavelength reference absorption cell utilizing acetylene may be used, however the hydrogen-cyanode cell has more lines across a bigger range. With a broadband input to the cell, the output displays the spectrum of the input with several narrow dips in the spectrum corresponding to the absorption lines. A photodetector sees the transmission spectrum of the absorption cell while another photodetector sees the Bragg gratings reflection from a sensing array. The filter drive voltages that coincide with the dips of the transmission spectrum are used to calibrate the voltage-to-wavelength function of the scanning filter. In this system, there is no temperature compensation step as the absorption lines are not sensitive to temperature.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1a shows a block diagram of a passive, temperature compensated device for a tunable filter calibration Bragg-grating utilizing a dual-substrate Bragg grating calibration system.

Figure 1b shows a functional relationship between control voltag and passband center wavelength.

Figure 1c shows the voltage peaks present in the amplifiers indicating Bragg gratings at different scanning voltage values.

Figure 1d shows passband wavelength (nm) as constructed from the filter control voltage at known wavelengths of Bragg gratings on a glass and aluminum substrate.

Figure 2a shows a block diagram of a Bragg grating interrogation system for a tunable filter calibration utilizing a hydrogen-cyanide wavelength reference absorption cell.

Figure 2b shows a normalized transmission spectrum.

Figure 2c shows a series of dips in voltage on amplifier A indicating absorption lines at different scanning voltage values (V_1 to V_n)(different passband wavelengths) and peaks in voltage (V_{FBG1} and V_{FBG2}) on amplifier B corresponding to gratings at two different wavelengths.

DESCRIPTION OF THE PREFERRED EMBODIMENT

The first preferred embodiment of a passive, temperature compensated device for a tunable filter calibration Bragg-grating **10**, as shown in **Figure 1**, is an array **12** of at least six Bragg gratings **14**, five Bragg gratings **14** are bonded to a common host substrate **16**, α_1, such as glass, with a single grating **18** bonded to a substrate **22**, α_2, material, with a different linear coefficient of thermal expansion, such as aluminum (α representing the coefficient of expansion). The gratings **16** and **22** are reference gratings **21**. The Bragg wavelength, λ_B, of an unbonded grating will vary with temperature due to changes in the index of refraction of a fiber core, d_n, and the expansion/contraction of the glass fiber itself according to

$$\Delta\lambda_B = [(d\Lambda/dT)/\Lambda + (dn/dT)/n]\lambda_B\Delta T \qquad (1)$$

where Λ is the period of the index-modulation of the fiber core, which creates the grating. The $(d\Lambda/dT)/\Lambda$ term is simply the thermal coefficient of linear expansion. For silica the dn/dT term dominates the thermal wavelength shift effect. When bonded to a substrate **16** or **22**, the changes in length due to temperature can be amplified, where $(d\Lambda/dT)/\Lambda$ is replaced by the expansion coefficient of the substrate which can be much higher. By bonding two gratings **12** and **18** to two different substrates **16** and **22** with differing expansion coefficients, changes in the common temperature of the substrates **16** and **22** can be measured by monitoring the difference between shifts of the grating wavelengths according to

$$\Delta T = (\Delta\lambda_{B1} - \Delta\lambda_{B2})/\left\{\lambda_{B1}[\alpha_1 + (dn/dT)/n] - \lambda_{B2}[\alpha_2 + (dn/dT)/n]\right\} \qquad (2)$$

when it is assumed that the coefficients of the substrates, α_1 and α_2, are well known, and the Bragg wavelengths are known prior to the change in temperature.

Equation (2) is used first to estimate the temperature of an array of the gratings **12** with the estimated temperature, the present wavelengths of the gratings **14** being estimated from

$$\lambda_{Bi} = \lambda_{Bi}\big|_{T=To} + \lambda_{Bi}[\alpha_i + (dn/dT)/n](T - T_0) \qquad (3)$$

where T_0 is the temperature at which λ_{Bi} is initially measured, and i refers to the grating number.

Wavelength-shift detection systems use scanning bandpass filters to measure grating wavelengths according to the control voltage applied to the filter at the same time the grating wavelength and passband wavelength coincide. The relationship between control voltage and passband center wavelength is typically nonlinear. For example, a scanning Fabry-Perot filter is often used in these applications. **Figure 1b** illustrates the functional relationship between control voltage and passband center wavelength. Furthermore, the function often encounters a drift over even short time periods such that after several minutes the curve may shift from the solid line **24** to the dotted line **26**. In this case, a continuously updated calibration curve is necessary to ensure an accurate wavelength-to-voltage mapping that is needed for wavelength- shift accuracy as well as low frequency, absolute wavelength monitoring.

The scanning filter **28** filters a broadband source of optical light **32** generated by an optical light source **76** so that at any point in time only a narrow band of light is present in the grating-containing fibers **32** that are connected to the output of the filter **28** through 50/50 couplers **34**. In this embodiment light is only returned to photodetectors A **36** and B **78** when the passband is scanned through the wavelength of a grating **14** or **18**, and the gratings **14** and **18** reflects back through the coupler **34** to the detector **38** then amplified in an associated amplifier

42. The amplified photodetector signal **37** results in a series of peaks that correspond to the gratings `**14** Or **18** in the arrays **12** and **22** from the lowest wavelength to highest as the drive voltage **44**, V(t), is increased. In this embodiment **10**, one grating array **12** contains the calibration and reference device **16** and **22**, while the other array **98** is considered an array of sensing gratings **102** and **104**. The sensing grating, for example, may be bonded to a bridge girder. To know the Bragg wavelength of these gratings it is necessary for the calibration/reference device have a high accuracy.

The following steps are used in the first preferred embodiment **10** to determine the reference wavelengtrhs and the scanning filter calibration curve and finally the wavelengths of the sensing Bragg gratings **102** and **104**. As the filter voltage **44** is scanned from its lowest to highest voltage, the voltages at which the reference gratings **21** are encountered, V_1 **52** - V_2 **54** are recorded, as shown in **Figure 1c**. V_7 **46** and V_8**48** denote the voltages at which the sensing gratings **102** and **104** are encountered. The 2nd lowest wavelength, λ_2, corresponds to the grating **18** which is attached to a substrate **22** different from the rest of the reference grating **14**. In this example this grating **18** is bonded to an aluminum strip while the other gratings **14** are bonded to a glass slide. When the temperature of the substrates **16** and **22** change together (they are in thermal contact) the aluminum-bonded grating **18** sees more expansion and compression than the glass-bonded gratings **14**, Correspondingly, the ratio

$$R = (V_2 - V_1)/(V_3 - V_1) \qquad (4)$$

increases as temperature T increases. If the lowest three Bragg wavelength, λ_1 **52** through λ_3 **56** are chosen to be within a few nanometers of each other, as shown in **Figure 1d**, R is well approximated to be linear and is independent of the peak-to-peak amplitude of the filter drive voltage **44**. R is typically measured directly by placing the reference device **14** and **18** in an environmental chamber and recording R as T is varied through a wide range. With this calibration curve, T can be approximated by calculation of R with every sweep of the filter **48**. Once T is acquired the glass-bonded and aluminum-bonded gratings **14** and **18**, respectively, wavelengths are calculated from Equation (3) to obtain λ_1 through λ_6. At this point the voltages V_1 **52** through V_6 **64** are used with the λ's to calculate the voltage-to-wavelength function for the scanning range of the filter **28**. For scanning Fabry-Perot filters **28**, the function is well approximated by a 3rd order polynominal. With the function estimated, the wavelength of the sensor gratings λ_7 **102** and λ_8 **104** in **Figure 1a**, are calculated from the voltages V_7 **46** and V_8 **48**. To compensate for variations in the calibration curve and temperature variations of the calibration array, the temperature is estimated and the function recalculated at every pass of the scanning filter **28** by the associated processing electronics **39**.

In a second preferred embodiment **20**, as shown in **Figure 2a**, a hydrogen-cyanide ($H^{14}C^{13}N$) wavelength reference absorption cell **66** is used. The gas is held in a pressurized cylinder with a fiber optic input **68** and output **72**. The cell **66** absorbs light at discrete wavelengths corresponding to the molecular vibrational mode frequencies of the gas. With a broadband optical light **74**, from a broadband optical light source **78**, input to the cell **66** in the range of 1525 to 1565 nm wavelengths, the output **72** displays the spectrum of the input **68** with several narrow dips in the spectra corresponding to the absorption lines. The normalized transmission spectrum is shown in **Figure 2b**. Twenty-one of the lines have a center wavelength uncertainty of less than +/- 0.0006 nm. Extreme variations in temperature (+/- 100K) only shift the wavelengths by 8.0×10^{-6} nm, hence for most applications, the lines may be assumed to be stationary with changes in temperature, The gas cells **66** are commercially available from such source as a HCN Optical Cell manufactured by Technical Glass, Inc. of Aurora, CO, and are fiber-pigtailed by the vendor.

To use the absorption cell **66** as a wavelength reference and filter calibration tool in fiber Bragg grating applications, photodetector A **36** sees a transmission spectrum of the absorption cell **66** while photodetector B **78** sees the Bragg grating reflections from the sensing array **82**. Similar to the teachings of the first preferred embodiment **10**, the filter drive voltages V_1 **82** through V_n **122**, as shown in **Figure 2c**, that coincide with the location of dips in the transmission spectrum (at known wavelengths) are used to calibrate the voltage-to-wavelength function of the scanning filter **28**. As opposed to the dual-substrate Bragg grating calibration taught in the first preferred embodiment **10**, this embodiment **20** has no temperature compensation step because the absorption lines are not temperature sensitive. The sensing grating **82** wavelengths are estimated from the voltages at their peak values, V_{FBG1}**124** and V_{FBG2}**126**, as shown in **Figure 2c**, and the calibration function.

Both embodiments **10** and **20**, may be applied to tunable filters other than the fiber Fabry-

Perot filters taught herein. Additionally, the placement of the filter **28** and sensing array **82** may vary in their placement in the optical system, for example the sensing array **82** may be placed in series with the gas cell **66** or dual-substrate grating array **16** and **22**.

Although the invention has been described in relation to an exemplary embodiment thereof, it will be understood by those skilled in the art that still other variations and modifications can be affected in the preferred embodiment without detracting from the scope and spirit of the invention as described in the claims.

ABSTRACT OF THE INVENTION

A passive, temperature compensated tunable filter calibration device for a Bragg grating interrogation system. In a first system, a dual-substrate Bragg grating calibration system, the temperature of an array of gratings is estimated using an array of gratings bonded to a common host substrate and a single grating bonded to a material with a different coefficient of thermal expansion. Changes in a common temperature of the substrates is measured by monitoring the difference between shifts of grating wavelength. As a filter voltage is scanned from its lowest to its highest voltage, the voltages are recorded. The second lowest wavelength corresponds to the grating attached to the differing substrate. The voltages are used to calculate a voltage-to-wavelength function for the scanning range of the filter. To compensate for variations in a calibration curve and temperature variations of the calibration array, the temperature is estimated and function re-calculated at every pass of the scanning filter. In a second system, a hydrogen-cyanide wavelength reference absorption cell that absorbs light at discrete wavelengths corresponding to the molecular vibrational mode frequencies of the gas. With a broadband optical light input to the cell, the output displays the spectrum of the input with several narrow dips in the spectra corresponding to the absorption lines of the cell. A first photodetector sees the transmission spectrum and a second sees the reflections from Bragg gratings in a sensing array. The filter drive voltages that coincide with the dips of the transmission spectrum are used to calibrate the voltage-to-wavelength function of the scanning filter. In this system there is no temperature compensation step as the absorption lines are not sensitive to temperature.

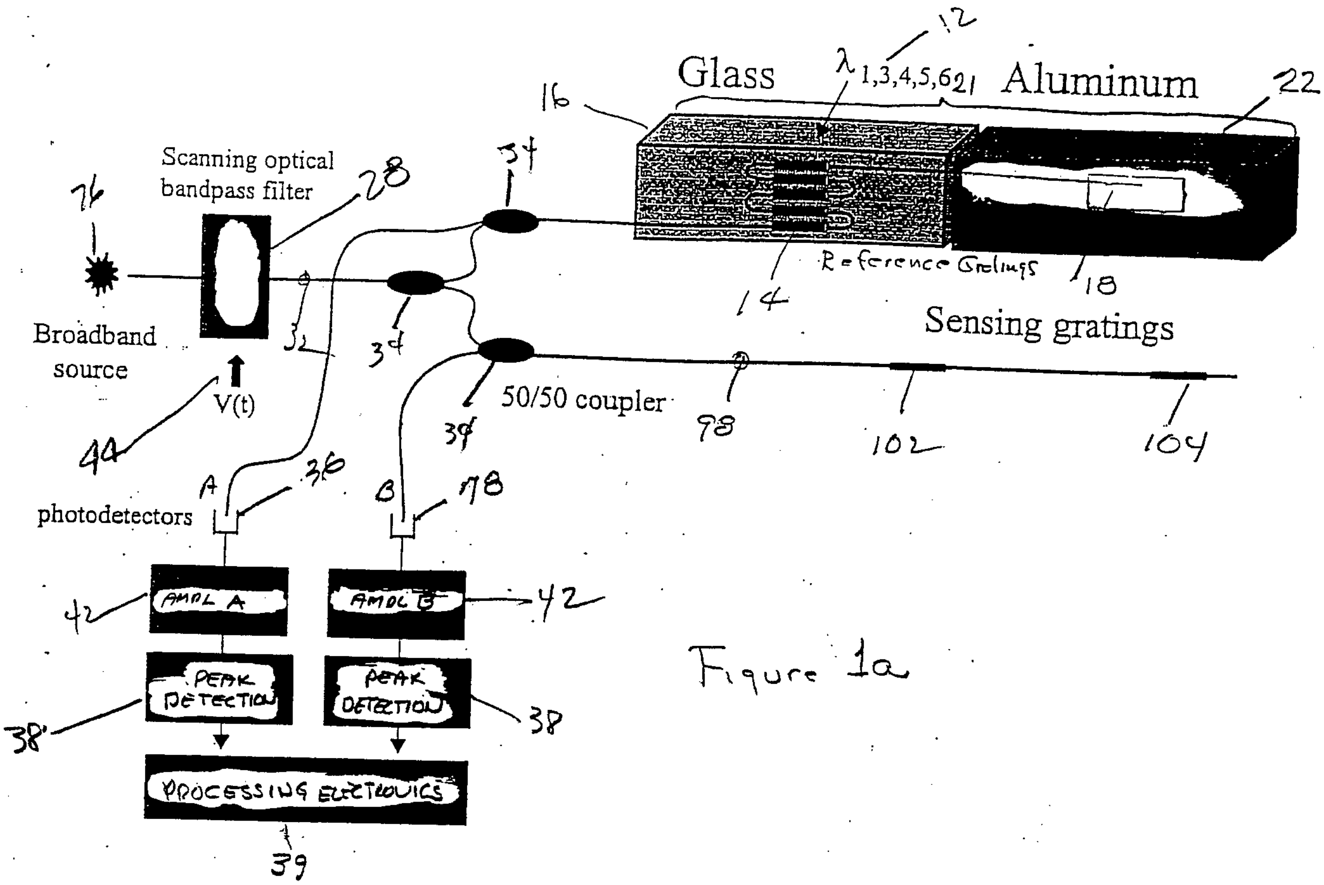


Figure 1a

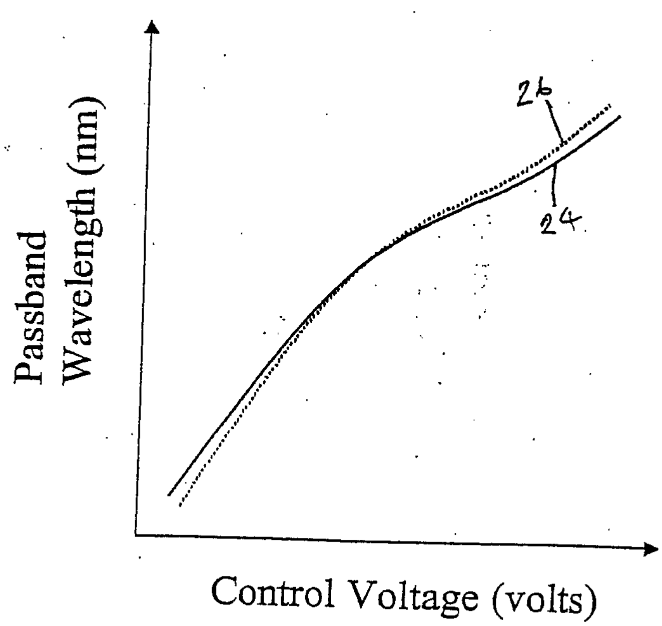


Figure 1b

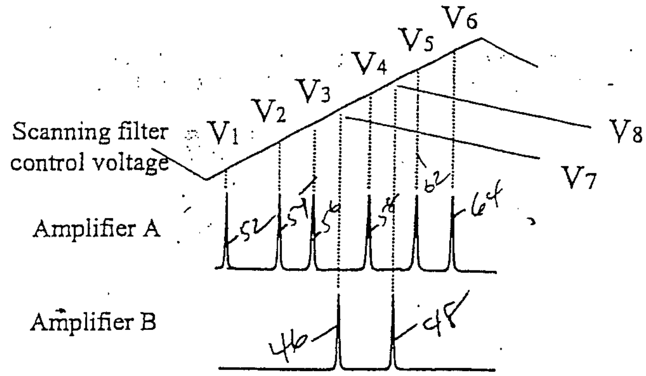


Figure 1c

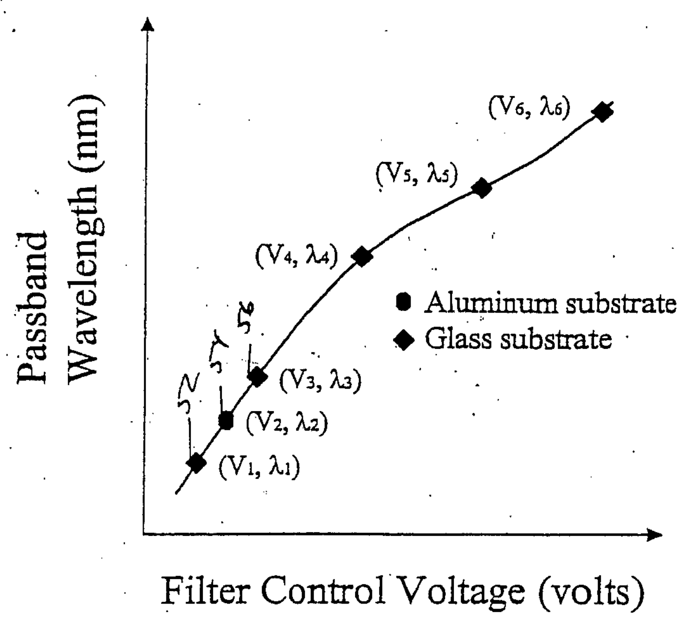


Figure 1d

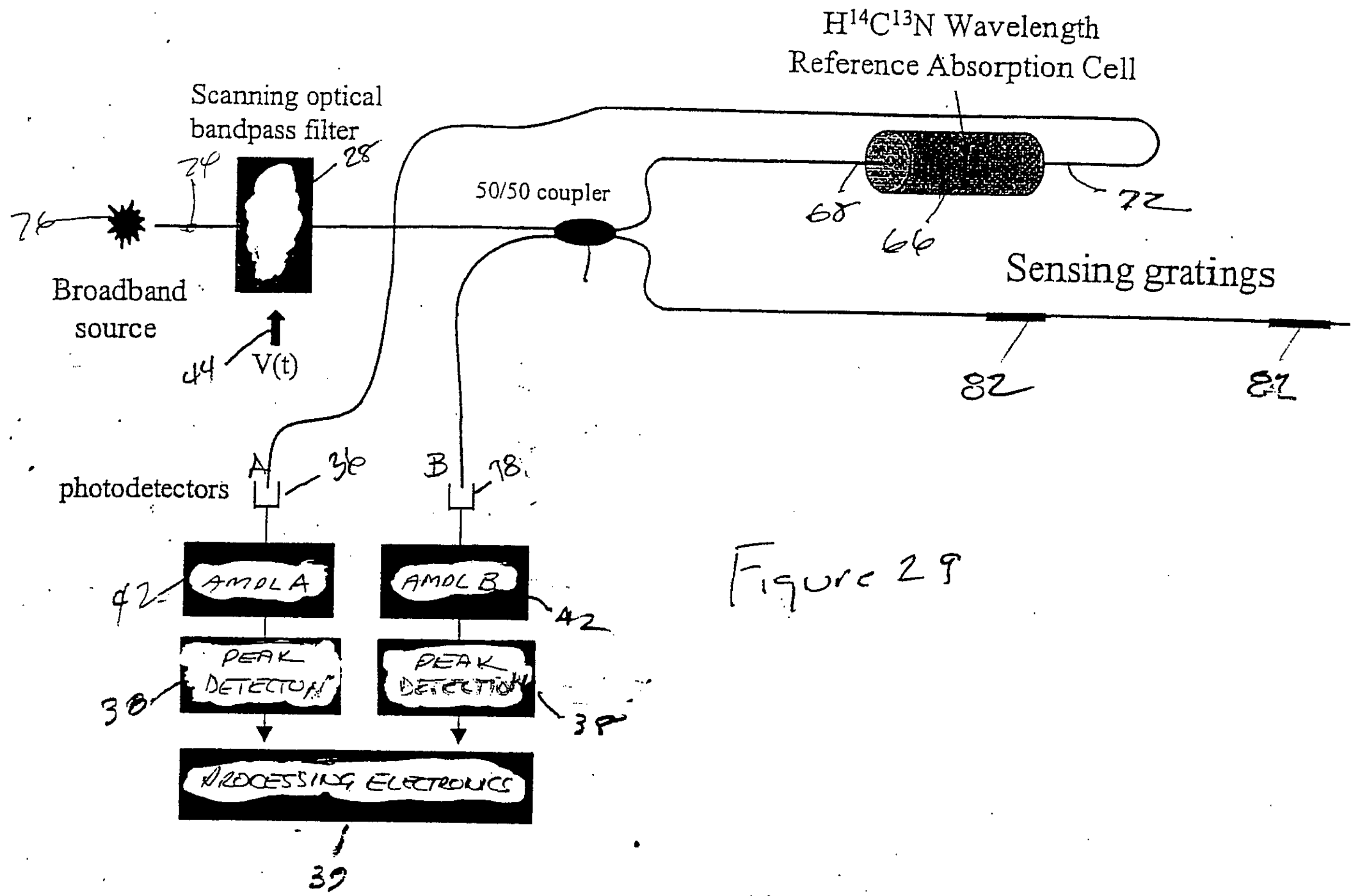


Figure 2a

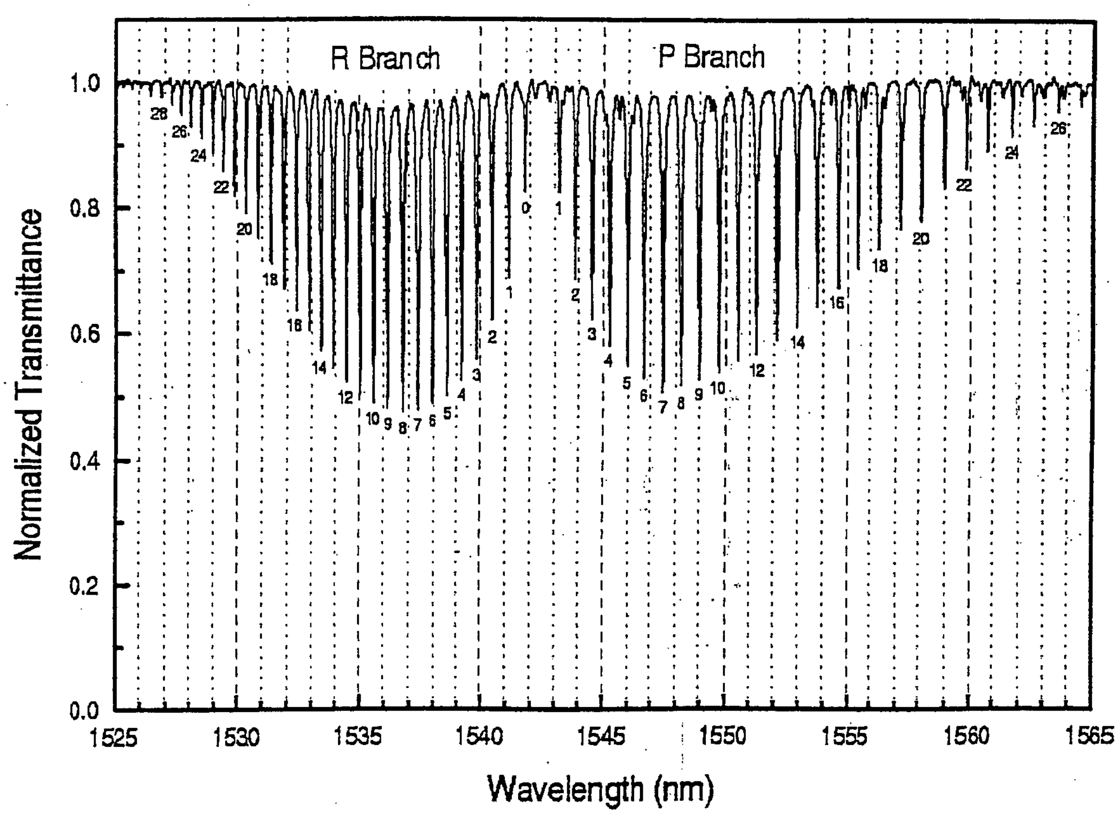
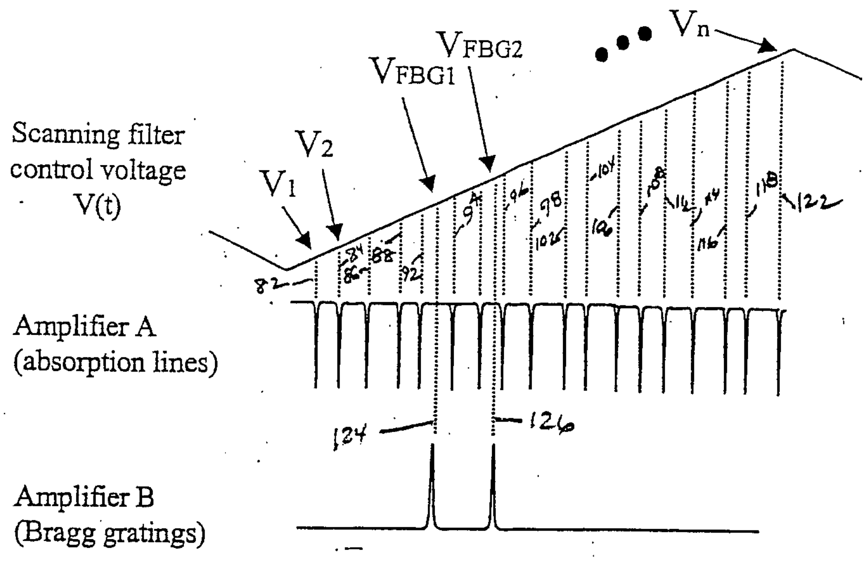


Figure 2b



Scanning filter control voltage V(t)
V_1
V_2
V_{FBG1}
V_{FBG2}
V_n
82
84
86
88
92
94
96
98
102
104
106
108
112
114
116
118
122
Amplifier A (absorption lines)
124
126
Amplifier B (Bragg gratings)

Figure 2c